Fabrication and Characterization of Microstructured Magnetic Tunnel Junction Rings

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Microstructured magnetic tunnel junction rings have been fabricated by a top-down technique combining electron beam lithography and ion milling process. Four-terminal magnetoresistance measurements and magnetic force microscopy were used to successfully explore a four-transition process within the free layer throughout the magnetization reversal. Various magnetization configurations were identified to be the onion state, vortex-pair state, vortex state, vortex-core state, and reverse onion state. In addition, the various durations of each magnetic state observed in the magnetoresistance curve can be utilized for the study of a coupling effect between the pinned layer and the free layer.

***Index Terms*—Fabrication, magnetic force microscopy (MFM), magnetization reversal, magnetoresistance.**

I. INTRODUCTION

OVER the years, magnetic random access memories have received a great deal of attention due to predominant advantages, such as energy efficiency and nonvolatility [1]–[3]. Many efforts were then paid to a thorough investigation of magnetic multilayer structures for higher magnetoresistance ratio and various shapes of patterned elements for simple and reversible switching processes. In general, elliptically elongated memory cells in conjunction with synthetic antiferromagnetic (SAF) free-layer structures were long adopted to effectuate robust switching characteristics and an ultrahigh density goal. Until a few years ago, another approach was first proposed by Zhu [4] who came up with the idea of using an annual shape for a memory cell. However, most of the previous studies on ferromagnetic rings often focused on the switching characteristics of single permalloy or cobalt rings [5]–[7]. Nevertheless, cell configurations with the current perpendicular to the plane (CPP) multilayer systems using either giant magnetoresistance (GMR) or tunneling magnetoresistance (TMR) play an important role for the applications of magnetoresistive random access memory (MRAM). Recently, Zhu's group for the first time realized the concept in CPP-GMR rings [8], revealing higher magnetoresistive (MR) response. Despite the relatively difficult fabrication process, the CPP-TMR system is expected to have better advantage, giving rise to a higher MR ratio, in comparison with the CPP-GMR system. Furthermore, this advantage even provides a highly sensitive way of exploring the magnetization difference between the free and pinned layer, and thus facilitates our investigation of metastable states during the reversal process of the free layer. Herein, we present a study of fabrication and characterization of magnetic tunnel junction (MTJ) rings. The main concerns are focused on the fabrication process as well as the free-layer behavior during the magnetization reversal of MTJ rings using four-terminal magnetoresistance measurements and magnetic force microscopy (MFM) in the presence of external magnetic fields.

II. EXPERIMENTS

The MTJ thin films consisting of Si/SiO$_2$ 50-substrate/Ta 5/Cu 20/Ta 5/NiFe 2/Cu 5/MnIr 10/CoFe 4/Al-N 1.5/CoFe 4/NiFe 20/Ta 5-cap (thickness in nanometers) were first prepared by the dc magnetron sputtering method [9]. A microstructured MTJ ring with outer diameter of 4 μm and inner diameter of 1 μm was fabricated using a top-down technique. Fig. 1 shows a series of schematics of fabrication process. First, the isolated bottom electrode was defined by photolithography and etched by ion milling with mask of photoresist AZ6112, shown in Fig. 1(a). After removing the photoresist, a hard mask of Ti with ring shape, i.e., the mask of MTJ ring cell, was created by standard electron beam lithography through a lift-off process, shown in Fig. 1(b). Then a two-step ion milling that was adopted to avoid edge shorting was utilized to transfer the ring pattern to the MTJ structure until the top of the bottom Cu layer, shown in Fig. 1(c). A stencil mask constructed by electron beam lithography and reactive ion etching with gas of CF$_4$ after SiN$_x$ sputtered onto a cell area was used to form the top contact trench of the cell, shown in Fig. 1(d). Finally, a top electrode of 1000 Å Au was deposited by thermal evaporation, shown in Fig. 1(e). The switching characteristic of the device was investigated using a typical four-terminal MR measurement and MFM.

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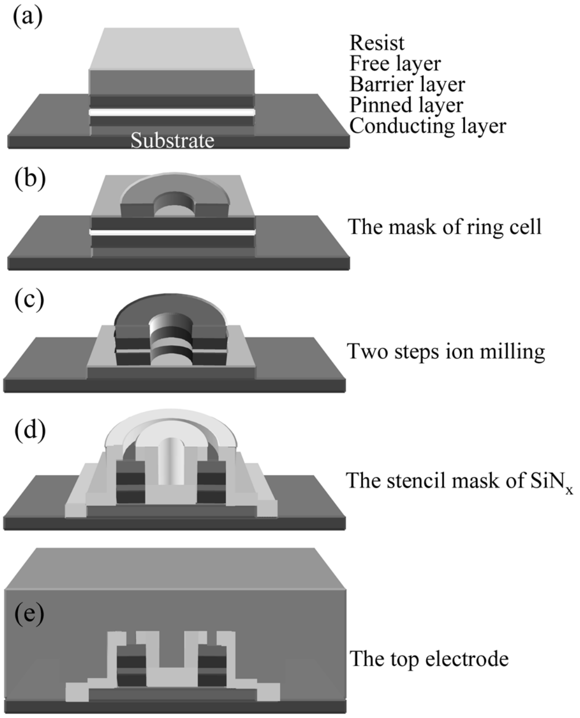


Fig. 1. Cross-sectional scheme of fabrication processes of a ring-shaped MTJ device.

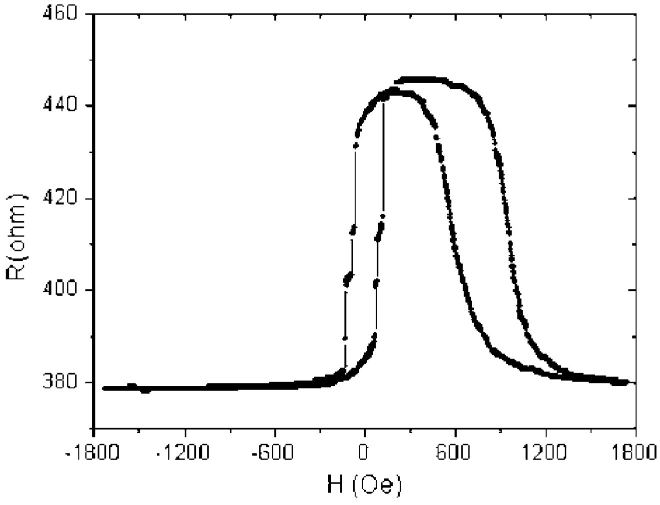


Fig. 2. MR curve of the ring-shaped MTJ device shows 16% MR ratio with $\mathrm{RA} \sim 17\ \mathrm{k}\,\Omega \times \mu\mathrm{m}^2$.

III. Results and Discussion

Fig. 2 shows a magnetoresistance versus applied field curve measured with the external field applied along the biasing direction, in which the magnetization of the pinned layer is believed to be in the uniformly horizontal direction. The observed MR ratio of 16% is smaller than that of the big pattern device which is about 50% [9]. Whereas the biasing field of about 760 Oe stays virtually the same with the sheet film, data were extracted from M-H loop measured by alternating gradient magnetometry, revealing that the biasing effect did not change after patterning into the ring shape. This degeneration of MR ratio may be due to the effects of shape anisotropy and the edge's damage during the fabrication process. The most striking part is that there are discernible steps developed throughout the magnetization reversal, as shown in the MR minor loop of Fig. 3. These clear four-transition reversal processes may have resulted from a complex reversal process on the free layer, which was later confirmed with magnetic force microscopy.

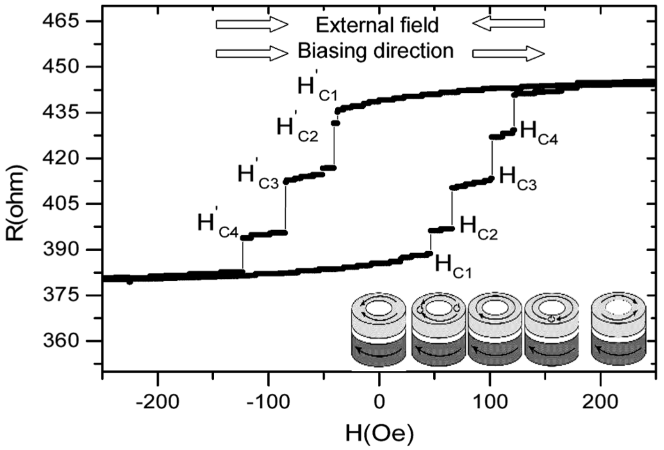
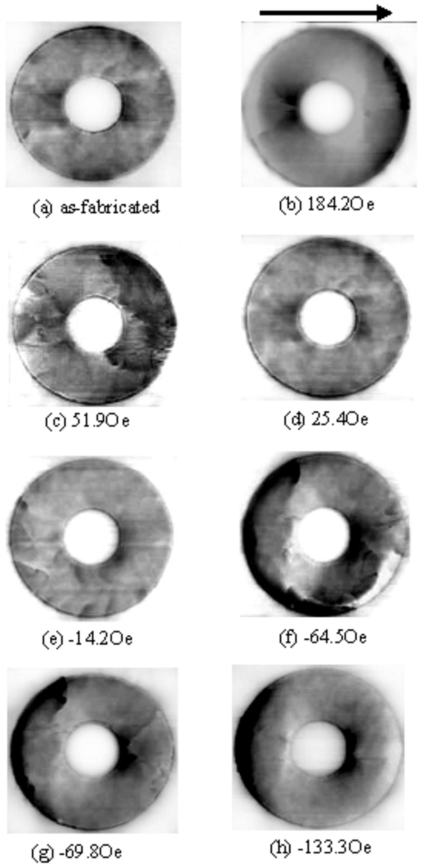


Fig. 3. MR minor loop reveals a clear four-transition reversal process. The upper inset indicates the directions of external field and biasing. The lower insets illustrate the magnetization configurations of free and pinned layers corresponding to the steps as the field in the sweep-up process. $H_{\mathrm{C}i}$ represents the field for each transition on the free layer. Note that the magnetization in the pinned layer is supposed to be in the uniformly horizontal direction.

A series of MFM images, shown in Fig. 4, taken *in situ* under the magnetic field range from $+184$ Oe to -133 Oe, may illustrate the magnetoresistance changes associated with the magnetization evolution of the free layer. The as-fabricated remanent state is shown in Fig. 4(a). An onion state shown in Fig. 4(b), with near 90° domain walls, is observed after saturation. Sequentially, the vortex walls come after the transverse walls to form the vortex-pair state shown in Fig. 4(c). The flux-closure vortex state, shown in Fig. 4(d), is favored due to the minimization of total energy. Via the so-called constrained vortex state [10] shown in Fig. 4(e) the ring enters the so-called vortex-core state shown in Fig. 4(f). Finally, the core is pushed out of the ring by a stronger field, shown in Fig. 4(g), and then the ring evolves into a reverse onion state, shown in Fig. 4(h). Similar results were obtained in a single-layered permalloy ring in our previous work [11]. A series of schematics, as shown in the inset of Fig. 3, are drawn to illustrate the magnetization reversal of a free and pinned layer in the field sweep-up process: the first transition represents vortex-pair state evolved from quasi-uniform onion state; the second one represents the annihilation of two vortex cores, forming a vortex state; the third increase in resistance is due to the nucleation of a vortex core in the ring; and the final transition is from vortex-core state to a reverse onion state.

The switching field of each transition can be definitely determined by the discontinuities in the MR minor loop. In the sweep-up field, the switching fields are: $H_{\mathrm{C}1} = 46$ Oe, $H_{\mathrm{C}2} = 65$ Oe, $H_{\mathrm{C}3} = 101$ Oe, and $H_{\mathrm{C}4} = 120$ Oe, whereas the switching fields are: $\acute{H}_{\mathrm{C}1} = -37$ Oe, $\acute{H}_{\mathrm{C}2} = -41$ Oe, $\acute{H}_{\mathrm{C}3} = -85$ Oe, and $\acute{H}_{\mathrm{C}4} = -122$ Oe in the sweep-down field. Notice that the coupling effect due to the pinning layer is so significant



(a) as-fabricated (b) 184.2Oe

(c) 51.9Oe (d) 25.4Oe

(e) -14.2Oe (f) -64.5Oe

(g) -69.8Oe (h) -133.3Oe

Fig. 4. MFM images of ring-shaped MTJ cell. The images were taken *in situ* under the magnetic field range from $+184$ Oe to -133 Oe after saturation field of 300 Oe. The arrow presents the field direction.

that the durations of individual metastable states in the sweep-up field are different from the ones in the sweep-down field. For instance, the duration of vortex-pair state in the sweep-up field is about 19 Oe; the one in the sweep-down field is less than 4 Oe. In a word, the magnetization of free layer is apt to be aligned with the one of pinning layer.

IV. CONCLUSION

To summary, the CPP microstructured MTJ rings have been successfully fabricated by a top-down process with special care taken in the ion milling process, and the high sensitivity based on the tunneling MR measurement empowers us to determine any possible transitions occurred throughout the magnetization reversal. In this case, a four-transition magnetization reversal was observed, and the coupling effect between the free layer and the pinned layer was also remarked. In addition to the MR measurements, MFM was adopted to inspect the magnetization configurations of the free layer such as onion, vortex-pair, vortex, vortex-core states, and reverse onion states, showing a substantial agreement with the transitions observed in the MR curve.

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